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CHAPTER 3

WORKING MEMORY

Alan Baddeley

How are you at mental arithmetic? Could you multiply 27 × 3? Try it.

Different people use different methods; in my own case, I multiplied the 7 by 3 resulting in 21, then held the 1 in mind and carried the two, before then going on to multiply 2 × 3, and so forth, interleaving the retrieval of numerical facts, with holding and manipulating the temporary totals. I had, in short, to use working memory, simultaneously holding and processing information. This active use of memory is the focus of the present chapter.

The idea that short-term memory (STM) serves as a working memory was proposed by Atkinson and Shiffrin (1968), who devised the model briefly described in Chapter 1. Because it had a great deal in common with many similar models that were popular at the time, it became known as the *modal model.*

As Figure 3.1 illustrates, the modal model assumes that information comes in from the environment and is processed first by a parallel series of brief temporary sensory memory systems, including the iconic and echoic memory processes discussed in Chapter 1. From here, information flows into the *short-term store*, which forms a crucial part of the system, not only feeding information into and out of the *long-term store*, but also acting as a *working memory*, responsible for selecting and operating strategies, for rehearsal,

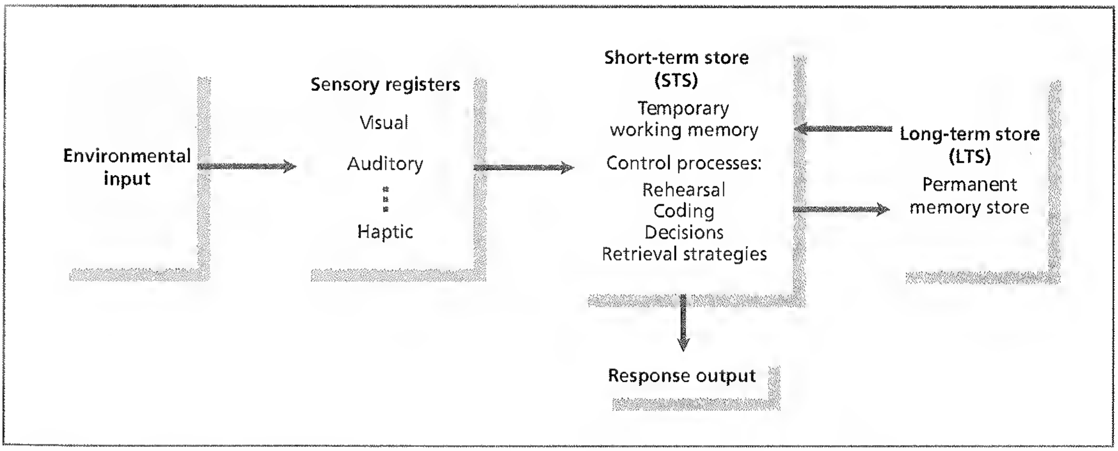


Figure 3.1 The flow of information through the memory systems as conceived by Atkinson and Shiffrin's modal model. Copyright © 1971 Scientific American. Reproduced with permission.

and generally serving as a global workspace. Atkinson and Shiffrin (1968) created a mathematical simulation of their model, concentrating on the processes involved in the rote rehearsal of verbal items and on the role of rehearsal in the transfer of information from the short-term to the long-term store. For a while, the modal model seemed to offer a neat solution to the question of how information is manipulated and stored. Before long, however, problems began to appear.

One problem concerned the assumption that simply holding items in the short-term store would guarantee learning. This view was challenged by Craik and Lockhart (1972), who proposed instead the principle of **levels of processing**, which maintains that learning depends on the way in which material is processed, rather than time in short-term storage. This important theory is discussed in Chapter 5.

The Atkinson and Shiffrin model also had difficulty in accounting for some of the neuropsychological evidence. You may recall that Shallice and Warrington (1970) described a patient who appeared to have a grossly defective short-term store. According to the modal model, the short-term store plays a crucial role in transferring information into and out of long-term memory (LTM). This STM deficit should therefore lead to greatly impaired long-term learning in such patients. Furthermore, if the short-term store acts as a general working memory, these patients should suffer severed disruption of such complex cognitive activities as reasoning and comprehension. This was not the case. One patient with grossly impaired STM was a very efficient secretary, another ran a shop and a raised family, and a third was a taxi driver (Vallar & Shallice, 1990). In short, they showed no signs of suffering from a general working-memory deficit.

Within a very few years, the concept of STM had moved from simplicity to complexity. A wide range of new experimental techniques had been invented, but none of them mapped in a simple straightforward way onto any of the original theories proposed to account for the wide range of studies of STM. At this point, many investigators abandoned the field in favor of the study of LTM, opting instead to work on the exciting new developments in the study of levels of processing and of semantic memory.

At just the point that problems with modal model were becoming evident, Graham Hitch and I were beginning our first research grant in which we had undertaken to look at the relationship between STM and LTM. Rather than attempt to find a way through the thicket of experimental techniques and theories that characterized both fields, we opted to ask a very simple question, namely, if the system or systems underpinning STM have a function, what might it be? If, as was generally assumed, it acted as a working memory, then blocking it should interfere with both long-term learning and complex cognitive activities such as reasoning and comprehending. Not having access to patients with this specific STM deficit, we attempted to simulate such patients using our undergraduate students, a process that happily did not require physical removal of the relevant part of their brain, but did involve keeping it busy while at the same time requiring participants to reason, comprehend, and learn (Baddeley & Hitch, 1974).

Virtually all theories agreed that if verbal STM was characterized by any single task, that task was digit span, with longer sequences of digits occupying more of the capacity of the underlying short-term storage system. We therefore combined digit span with the simultaneous performance of a range of other tasks such as reasoning, learning, and comprehension, which were assumed to depend on this limited-capacity

KEY TERM

Levels of processing: The theory proposed by Craik and Lockhart that asserts that items that are more deeply processed will be better remembered.

system. Participants were given a sequence of digits that they were continually required to rehearse out loud at the same time as they were performing other cognitive tasks. By varying the number of digits being held, it should be possible to vary the demand on this limited-capacity system. If it did indeed reflect a working memory responsible for reasoning and other tasks, then the longer the sequence, the greater the digit load and the greater the interference should be.

One experiment involved presenting a simple reasoning task in which students had to verify a statement about the order of two letters. The task is shown in Box 3.1. Try it yourself.

Somewhat to our surprise, people were able to do this, even when holding simultaneously and repeating sequences of up to eight digits, beyond memory span for many of those tested. As Figure 3.2 shows, average time to verify the sentences increased systematically with digit load, but not overwhelmingly so. The total time taken with eight digits was about 50% more than baseline. Perhaps more remarkably, the error rate remained constant at around 5%, regardless of concurrent digit load.

What are the implications of these results for the view that the short-term store serves as a working memory? The error rate suggests that performance can go ahead quite effectively regardless of concurrent digit load, whereas the processing time data suggest that there is *some* involvement, although not of overwhelming magnitude. Results from studies of learning and comprehension gave broadly equivalent results (Baddeley & Hitch, 1974), supporting some kind of working memory hypothesis, but not one that depended entirely on the memory system underpinning digit span.

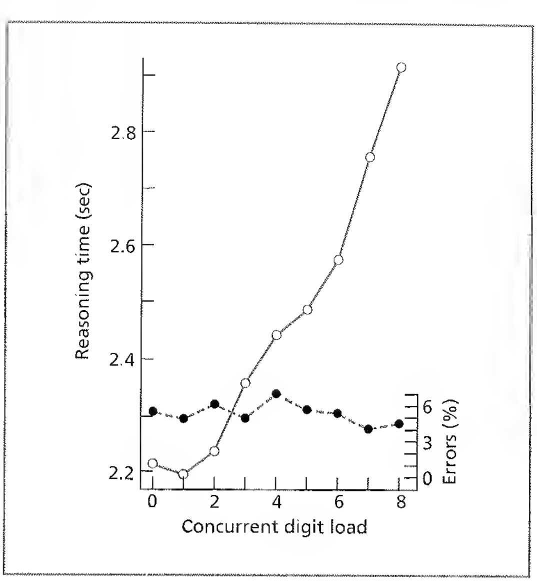


Figure 3.2 Speed and accuracy of grammatical reasoning as a function of concurrent digit load. From Baddeley (1986). Copyright © Oxford University Press. Reproduced with permission.

Box 3.1 Examples from the grammatical reasoning test used by Baddeley and Hitch (1974).

		True	False
A follows B	B → A		
B precedes A	A → B		
B is followed by A	B → A		
A is preceded by B	B → A		
A is not preceded by B	A → B		
B does not follow A	A → B		

Answers: T, F, T, T, T, F.

We therefore proposed a somewhat more complex model, which we called *working memory*, a term invented but not further elaborated by Miller, Galanter, and Pribram (1960). The emphasis on "working" aimed to dissociate it from earlier models of STM, which were primarily concerned with storage, and to emphasize its functional role as a system that underpins complex cognitive activities, a system that supports our capacity for mental work and coherent thought (Baddeley & Hitch, 1974).

THE MULTICOMPONENT MODEL

The model we proposed had three components (Figure 3.3); one of these, the **phonological loop**, is assumed to be specialized for holding sequences of acoustic or speech-based items. A second subsystem, the **visuo-spatial sketchpad** performs a similar function for visually and/or spatially encoded items and arrays. The whole system is controlled by the *central executive*, an attentionally limited system that selects and manipulates material in the subsystems, serving as a controller that runs the whole show. One way of gaining a feeling for the concept is to try the following: Think of your current house or apartment, and work out how many windows it has. Then move on to the next paragraph.

How many windows? How did you reach that number? You probably formed some sort of visual image of your house; this relies on the sketchpad. You presumably then counted the windows verbally using the phonological loop. Finally, throughout this process there was a need for your central executive to select and run the strategy. These three components of working memory will be considered in turn, beginning with the phonological loop, which—as mentioned previously—could be regarded as a model of verbal STM embedded within a more general theory of working memory.

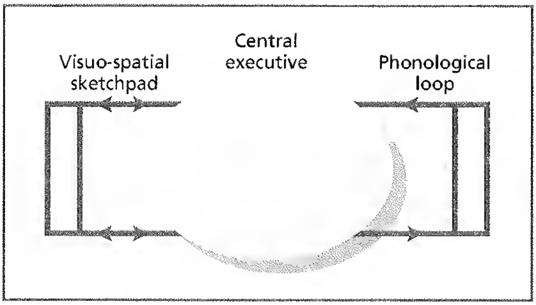


Figure 3.3 The initial Baddeley and Hitch working memory model. The double arrows are intended to represent parallel transfer of information to and from the sketchpad, and the single arrows the serial rehearsal process within the phonological loop. Based on Baddeley and Hitch (1974).

The phonological loop

As we saw in Chapter 2, the phonological loop is basically a model of verbal STM. It accounts for a wide and rich range of findings using a simple model that assumes a temporary store and a verbal rehearsal process. It is not free of critics, but has proved fruitful for over 30 years without—so far—being replaced by a widely accepted better model. But how does it fit into the broader context of working memory? What is it for?

What use is the phonological loop?

On the evidence presented, the phonological loop simply increases span by two or three items on the rather artificial task of repeating back numbers. So what, if any, is its evolutionary significance? Has evolution thoughtfully prepared us for the invention of the telephone? And if not, is the loop anything more than "A pimple on the anatomy of cognitive psychology," as suggested by one critic?

In an attempt to answer this question, two Italian colleagues, Giuseppe Vallar and Costanza Papagno, and I began to study a patient—PV—who had a very pure phonological loop deficit. Her digit span was two items but her intelligence, LTM, and short-term visual memory were excellent. She spoke fluently and her general language skills seemed normal. PV ran a shop, successfully raised a

KEY TERMS

Phonological loop: Term applied by Baddeley and Hitch to the component of their model responsible for the temporary storage of speech-like information.

Visuo-spatial sketchpad: A component of the Baddeley and Hitch model that is assumed to be responsible for the temporary maintenance of visual and spatial information.

family, and seemed to have few problems in her everyday life. Did she have any areas of major difficulty? If she did, this would give us a clue as to what function was served by her defective phonological loop.

We began with the hypothesis that the loop might have evolved to assist language comprehension (Vallar & Baddeley, 1987). PV did have some problems, but only with a particular type of long sentence, where it is necessary to hold on to the first few words until the end of the sentence in order to understand it. This was not enough to create problems for PV in everyday life, and it is hard to see evolution favoring the development of a special subsystem to facilitate long-winded communication.

A second hypothesis was that the phonological loop system has evolved to help us learn language. People who have acquired a phonological loop deficit when adult, as is the case for PV, would experience few difficulties because they would already have mastered their native language. However, if they were required to learn a new language, they might have problems. We investigated this by requiring PV to learn to associate each of eight Russian words with their equivalent in Italian, PV's native language (Baddeley, Papagno, & Vallar, 1988). With spoken presentation, after ten trials, all of the control participants had learned all eight Russian words, whereas PV had not learned one (Figure 3.4). Could it simply be that she was amnesic? This was not the case, as when the task involved learning to associate two unrelated native language words such as *castle-bread*, a task that typically relies on **semantic coding** (Baddeley & Dale, 1966), she was quite unimpaired. Our results thus lent support to the possibility that the phonological loop is involved in language acquisition.

However, while a single case can be extremely informative, it is possible that the individual might be highly atypical, and hence ultimately misleading. Given that STM-deficit patients are rare, we opted to test our hypothesis further by disrupting the phonological loop in normal participants who were attempting to learn foreign language vocabulary. We predicted that disrupting the loop would cause particular problems in learning foreign vocabulary, just as in the case of PV. In one study, articulatory suppression was used (Papagno, Valentine, & Baddeley, 1991). When participants were required continually to repeat an irrelevant sound during learning, this proved

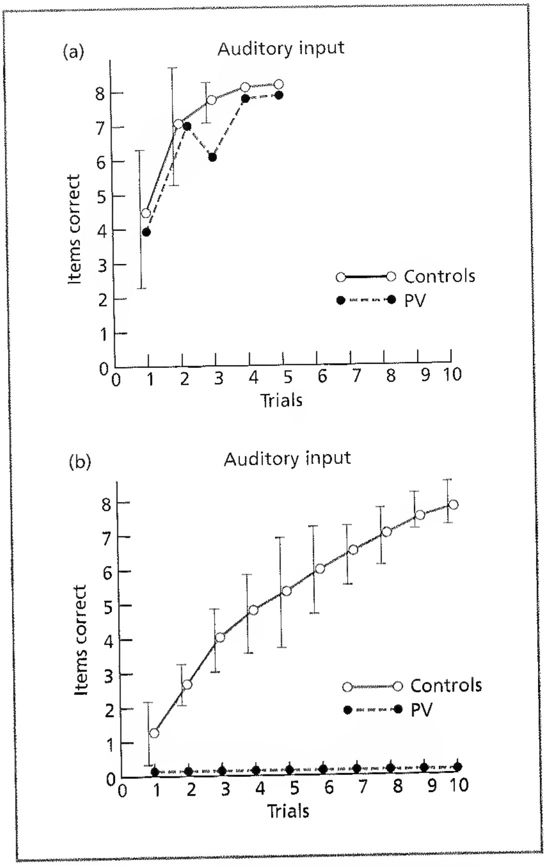


Figure 3.4 Rate of learning pairs of items by patient PV and controls. Her capacity to learn pairs of meaningful words was unimpaired (panel a), but she was not able to learn foreign language vocabulary (panel b). From Baddeley, Papagano, and Vallar (1988). Copyright © Elsevier. Reproduced with permission.

KEY TERM

Semantic coding: Processing an item in terms of its meaning, hence relating it to other information in long-term memory.

to disrupt foreign language learning, assumed to rely on the phonological loop, but had little effect on learning pairs of native language words. In another study, Papagno and Vallar (1992) varied either the phonological similarity or the length of the foreign words to be learnt, manipulating two factors known to influence the phonological loop. When the responses were foreign words, then similarity and length impaired performance to a much more substantial extent than occurred when both words were in the native language of the participants. The conclusions drawn from PV of the importance of the loop for learning new word forms therefore appeared to be supported. However, they still were confined to adults acquiring a second language. The system would clearly be more important if it also influenced the acquisition by children of their native tongue.

Susan Gathercole and I investigated this question by testing a group of children with a specific language impairment (Gathercole & Baddeley, 1990). These children were 8 years old, had normal nonverbal intelligence, but had the language development of 6-year-olds. Could this reflect a phonological loop deficit? When given a battery of memory tests, they proved to be particularly impaired in their capacity to repeat back unfamiliar pseudo words. Note that this task not only requires participants to hear the nonwords, but also to hold them in memory for long enough to repeat them. On the basis of this, we developed the **nonword repetition test** in which pseudo words of increasing length are heard and must be repeated (e.g. *ballop*, *woogalamic*, *versatrational*). We tested language-impaired children, other children of the same age with normal language development, and a group of 6-year-olds who were matched for level of language development with the language-impaired group but who, being younger, had a lower level of nonverbal performance. The results are shown in Figure 3.5, from which it is clear that the language-disordered 8-year-old children perform more poorly even than the 6-year-olds. In fact, they were equivalent to 4-year-olds in their nonword repetition capacity. Could their poor nonword repetition performance be related to their delayed language development? Is level of vocabulary related to nonword repetition performance in normal children too?

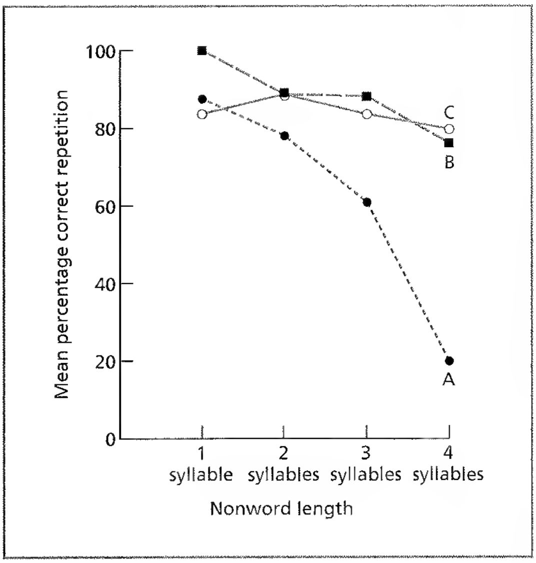


Figure 3.5 Percent correct repetition of nonwords by children with a specific language impairment (A), children of the same age (B), and children matched for language level (C). Adapted from Gathercole and Baddeley (1990).

In an attempt to investigate this, a cohort of children between the ages of 4 and 5 years who were just starting school in Cambridge, England, were tested using the nonword repetition test, together with a test of nonverbal intelligence and a measure of vocabulary. This involved presenting four pictures and pronouncing the name of one of them; the child's task was to point to the appropriate picture. As the test proceeded, the words became less and less common. Testing ended when performance broke down

KEY TERM

Nonword repetition test: A test whereby participants hear and attempt to repeat back nonwords that gradually increase in length.

because the child no longer knew the words. Performance on these three tests was then correlated to see to what extent vocabulary was related to intelligence and to nonword repetition. The results are shown in Table 3.1, from which it is clear there was a substantial correlation between the capacity to hear and echo back a word and level of vocabulary development.

Of course, correlation does not mean causation. It is just as plausible to assume that having a good vocabulary will help you repeat back unfamiliar sounds, as it is to assume that capacity for repeating unfamiliar sounds will help you acquire new vocabulary. A study of the development of vocabulary in 5- to 6-year-old children (Gathercole & Baddeley, 1989) suggested that phonological memory was indeed the crucial factor at this stage. However, as children become older they are increasingly able to use existing vocabulary to help learn new words (Baddeley, Gathercole, & Papagno, 1998). This is reflected in the fact that new words that contain letter sequences that resemble fragments of existing vocabulary (e.g. *contramponist*) are easier to repeat back than words that have a more unfamiliar letter structure (e.g. *skiticult*). However, future vocabulary is better predicted by performance on these unusual items. This is presumably because such items gain less support from existing vocabulary and hence continue to rely on the phonological loop (Gathercole, 1995). Whereas the link with vocabulary acquisition is probably the clearest evolutionary application of the phonological loop, it is likely that the loop also facilitates the acquisition of grammar, and probably also of reading (Baddeley et al., 1998). Indeed, the nonword repetition test is used widely in the diagnosis of dyslexia, although reduced phonological loop capacity is likely to represent only one of a range of variables that can impact on the complex skill of learning to read.

The phonological loop and action control

We have so far discussed the loop as a rather limited storage system that plays a relatively passive role in cognition. Miyake and Shah (1999b) suggested that this might well underestimate its importance, and this is proving to be the case. In one study, for example (Baddeley, Chincotta, & Adlam, 2001b), we were interested in the capacity to switch attention between two tasks. We used the simple task of adding or subtracting one from a series of digits, thus, given 8, the response should be 9 in one case and 7 in

Table 3.1: Relation between vocabulary scores at age 4 and other variables. There is a strong relationship with nonword repetition performance. From Gathercole and Baddeley (1989).

Measures	Correlation coefficient	Simple regression (% variance)	Stepwise regression (% variance)
Chronological age	0.218	5[a]	5[a]
Nonverbal intelligence	0.388	15[b]	13[b]
Nonword repetition	0.525	27[b]	15[b]
Sound mimicry	0.295	9[b]	0
Total	0.578	33[b]	—

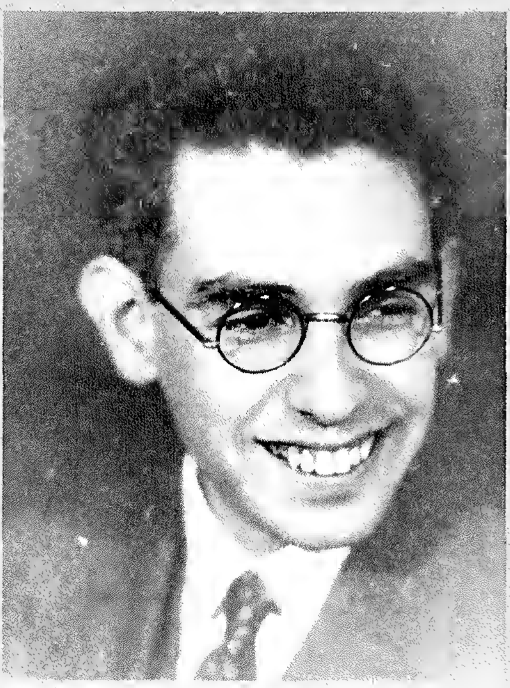
[a]$P < 0.05$; [b]$P < 0.01$.

the other. Participants were given a column of additions (e.g. 5 → 6: 8 → 9: 3 → 4, etc.), or a column of subtractions (e.g. 5 → 4: 8 → 7: 3 → 2, etc.), or were required to alternate, adding to the first, subtracting from the second, adding to the third etc. (e.g. 5 → 6: 8 → 7: 3 → 4, etc.). Alternation markedly slowed down performance, particularly when participants had to "remember" to switch, rather than having plus and minus signs beside each digit. However, performance was slower when participants had to suppress articulation while performing the switching condition, suggesting that they had been relying on a subvocal set of instructions to keep their place. Similar effects have been observed and investigated further by Emerson and Miyake (2003) and by Saeki and Saito (2004).

It is notable that participants in psychological experiments very frequently appear to rely on verbal coding to help them perform the task. This was investigated by two Russian psychologists—Lev Vygotsky (1962) and Alexander Luria (1959)—who emphasized the use of verbal *self-instruction* to control behavior, studying its application to the rehabilitation of brain-damaged patients and to its development in children (Box 3.2). Sadly, Vygotsky and Luria have so far had little direct influence on recent developments in cognitive psychology. One can only hope that further investigation of the role of speech in the control of action will remedy this.

We have described the development of the phonological loop model in some detail. This is not because it is the only, or indeed the most important, component of working memory; it certainly is not, but it is the component that has been investigated most extensively and, as such, provides an example of how relatively simple experimental tasks can be used to study

Box 3.2 Alexander Luria


Alexander Luria; 1902–1977.

The Russian psychologist Alexander Romanovitch Luria developed an ingenious method for studying the influence of language on the control of action. In one experiment, he asked children of different ages to squeeze a bulb when a red light came on, but not to squeeze for a blue light. Before the age of 3, children typically press in response to both lights, even though they can report the instruction correctly, and can perform it correctly if given the instruction "press" when the red light comes on but no instruction with the blue light. A few months later, they are themselves able to make the appropriate verbal responses, but still do not perform the action. By age 5, they are able both to speak and act appropriately, only later managing to act without giving themselves a verbal cue. Luria also demonstrated that patients with frontal-lobe damage could have difficulty with this task, and could be helped through verbal self-cueing.

complex cognitive processes and their practical implications.

We move on now to the visuo-spatial sketchpad, which has been rather less extensively investigated and will be described more briefly.

IMAGERY AND THE VISUO-SPATIAL SKETCHPAD

Suppose you were asked to describe a famous building such as the Taj Mahal. How would you do it? Try.

You probably based your description on some form of visuo-spatial representation, a visual image perhaps? An observer might also have seen you using your hands as a spatial supplement to your verbal account. People vary hugely in the extent to which they report having visual imagery. In the late nineteenth century, Sir Francis Galton, a Victorian gentleman, contacted his friends and asked them to remember their breakfast table from that morning, and then describe the experience. Some reported imagery that was almost as vivid as vision, whereas others denied having any visual imagery whatsoever. Such differences in reported vividness appear to have surprisingly little relationship to how well people perform on tasks that would be expected to make heavy demands on visual imagery, such as visual recall (Di Vesta, Ingersoll, & Sunshine, 1971). Those studies that have found any differences tend, somewhat surprisingly, to observe *poorer* performance on visual memory tasks by participants reporting strong visual imagery (Heuer, Fischman, & Reisberg, 1986; Reisberg, Clayton, Heuer, & Fischman, 1986). The reason for this unexpected finding appears to be that people with vivid imagery do not have better *memories*, but use vividness as a sign of the accuracy of their recall and are more likely to misjudge a vivid but erroneous memory to be correct. This suggests that subjective reports, however convinced we are about whether we do or do not have vivid imagery, might reflect the way in which we choose to categorize and describe our subjective experiences, rather than their content or capacity (Baddeley & Andrade, 2000).

How would you describe the Taj Mahal? Would vivid, visual imagery be the basis of your description?

Image manipulation

Figure 3.6 shows a task studied by Shepard and Feng (1972). If the shapes depicted were made out of paper, both could be folded to create a solid, with the shaded area being the base. Your task is to imagine folding the shapes (shown on the left-hand side of Figure 3.6) and decide whether the arrows will meet head on. Try it.

Shepard and Feng found that the time it took participants to come to a solution was systematically related to the number of folds that would have been required.

Tasks like this are often used to select people for jobs, such as architect and engineer, that are likely to involve visual or spatial thinking. They also tend to be somewhat better performed by men than by women, who are likely to use a more

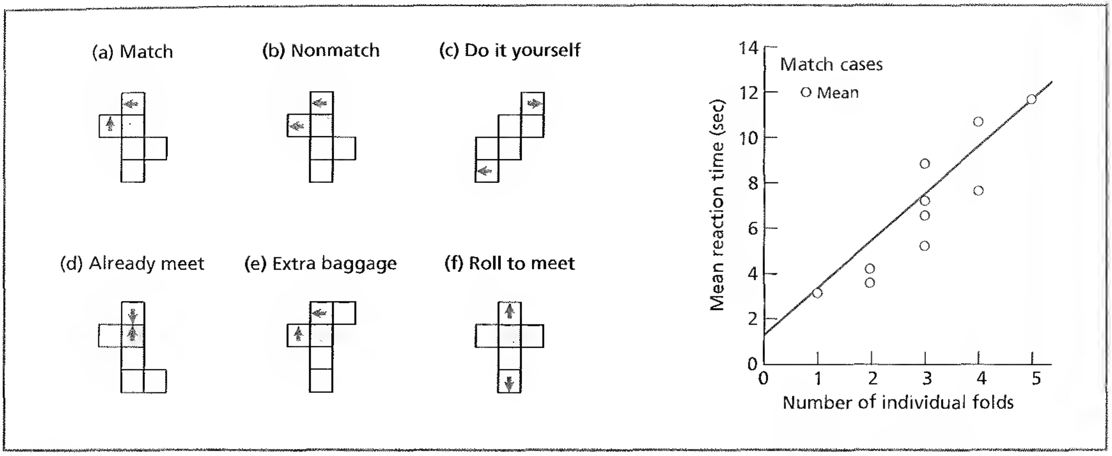


Figure 3.6 Left: Examples of six types of paper folding problems used by Shepard and Feng (1972). Your task is to decide what would happen if the shapes were folded and made into a cube. Would the arrows meet? Right: Average time to decide whether the arrows on the cubes would match as a function of number of imaginary folds necessary to reach that decision. The circles represent each of 10 different types of problem. Data from Shepard and Feng (1972).

analytic and piecemeal approach (Linn & Petersen, 1985). A subsequent study by Hsi, Linn, and Bell (1997) found that female University of California Berkeley engineering students were less good at performing a spatial manipulation test and were also likely to do less well on a difficult graphics course for which 25% of students obtained either a D or failed grade. Shi et al. spoke to experienced engineers about the strategies of spatial manipulation they used and, on the basis of this, produced a one-day intensive course on spatial manipulation strategies. This was highly successful in improving performance to a point at which the gender differences disappeared and virtually no failures occurred.

A number of studies have tried to study spatial manipulation within the laboratory. Finke and Slayton (1988) developed the following task:

First, form an image of the capital letter J. Then imagine capital D. Now rotate the D through 90 degrees to the left and place it on top of the J. What does it look like?

The answer is an umbrella. Pearson, Logie, and Gilhooly (1999) tried to analyze in more detail the processes involved. They gave their participants four, six, or eight symbols (e.g. square, triangle, circle, etc.), requiring them to use them to create an object that they should then name, and afterwards draw. If they had failed to produce an object after 2 minutes, participants were required simply to recall the memorized symbols. The role of the visuo-spatial sketchpad and the phonological loop in the task was studied by means of concurrent tasks, using either articulatory suppression to disrupt the loop, or tapping a series of spatial locations to disrupt the sketchpad. Pearson et al. found that spatial tapping disrupted the capacity to create novel objects, suggesting that this aspect depends on the sketchpad, but had no effect on the capacity to remember what shapes were involved. However, the latter was disrupted by articulatory suppression, suggesting that the names of the shapes to be manipulated were held in the phonological loop.

The study by Pearson et al. is a good example of the way in which the visuo-spatial sketchpad and phonological loop can work together to enhance performance. A very striking example of this comes from a study using a group of Japanese experts in mental calculation who are very skilled at using the traditional calculating aid, the abacus, which involves manipulating beads within a framework. Hatano and Osawa (1983a, 1983b) studied calculators who were able to dispense with the actual abacus, relying instead on imagining the abacus. Experts can mentally add and subtract up to 15 numbers, each comprising from 5 to 9 digits. They also have extremely high digit spans, around 16 for forward and 14 for backward recall. However, their enhanced span was limited to digits. Their span for other verbal material, such as consonants, for which the abacus imagery could not be used, was no better than that of a control group. As would be expected if the experts were relying on visuo-spatial imagery, their digit span was markedly disrupted by a concurrent spatial task, unlike control participants, whose performance was more disrupted by articulatory suppression.

Just as spatial activity can disrupt imagery, so imagery can interfere with spatial processing. A striking example of this occurred when I was visiting the US. I was listening to an American football game between UCLA and Stanford and forming a clear image of the game while driving along the San Diego freeway. I suddenly realized that the car was weaving from lane to lane. I switched to music and survived and on returning to Britain decided to study the effect under slightly less risky conditions. One of the imagery tasks used is shown in Figure 3.7. A sequence of sentences is heard and must be repeated. When the sentences can be mapped onto the visual matrix, people are able to remember about eight instructions, compared to only six when spatial mapping is not feasible.

Unfortunately, my department did not own a driving simulator for use as the spatial task, so instead I used a pursuit rotor, an ancient piece of equipment in which the participant is required to perform a tracking task, keeping a stylus in contact with a moving spot of light. When performing this task, the imagery advantage enjoyed by the spatially imageable sentences disappears (Baddeley, Grant, Wight, & Thomson, 1973). The interference proved to be spatial in nature rather than visual, since performance was disrupted by the task of tracking the *location* of an *auditory* sound source while blindfolded, but not by making

		3	4
	1	2	5
		7	6
		8	

Spatial material
In the starting square put a 1.
In the next square to the *right* put a 2.
In the next square *up* put a 3.
In the next square to the *right* put a 4.
In the next square *down* put a 5.
In the next square *down* put a 6.
In the next square to the *left* put a 7.
In the next square *down* put an 8.

Nonsense material
In the starting square put a 1.
In the next square to the *quick* put a 2.
In the next square to the *good* put a 3.
In the next square to the *quick* put a 4.
In the next square to the *bad* put a 5.
In the next sqaure to the *bad* put a 6.
In the next square to the *slow* put a 7.
In the next square to the *bad* put an 8.

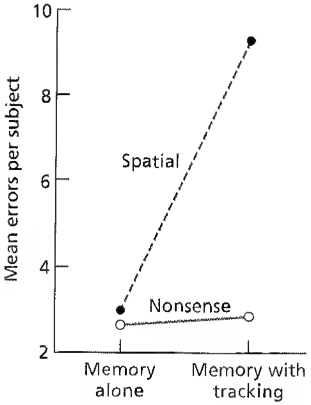


Figure 3.7 Left: Examples of the material developed by Brooks and used to study the visuo-spatial sketchpad. Participants must repeat the sentences from memory but can use the matrix to help them. Data from Brooks (1967). Right: The influence on recall of the Brooks sentences of a concurrent visuo-spatial tracking task. Data from Baddeley et al. (1973).

a *visual* but nonspatial brightness judgment (Baddeley & Lieberman, 1980).

Whereas this particular task appears to depend on spatial imagery, more purely visual imagery can also help in verbal recall. A powerful way of learning to associate pairs of words is to combine them into an interactive image; for example, to associate *violin* and *banana*, one might imagine a concert violinist using a large banana as a bow. Such object-based imagery tends to be disrupted by presentation of irrelevant pictures or colors, which participants are instructed to ignore (Logie, 1995). Indeed, under appropriate conditions, even a flickering dot pattern can disrupt the use of visual imagery (Quinn & McConnell, 1996a, 1996b).

Working memory and imagery

Virtually all the experimental work described so far focuses on the performance of tasks that are presumed to depend on visuo-spatial processing. However, investigators such as Shepard and Kosslyn avoid making any claims about how this relates to our subjective experience. A series of experiments by Jackie Andrade and myself tried to tackle this contentious problem, testing the hypothesis that visual imagery reflects the operation of the sketchpad, and auditory imagery the phonological loop (Baddeley & Andrade, 2000). We asked participants to form and judge the vividness of visual or auditory images. Participants were tested under baseline conditions, or under either articulatory suppression, which was predicted to make auditory imagery seem less vivid, or with a concurrent spatial tapping task known to disrupt visuo-spatial imagery. When the images were of novel material that had just been presented, comprising sequences of tones or arrays of shapes, our predictions worked well, with auditory imagery appearing less vivid under articulatory suppression, and visual imagery under spatial tapping. However, when the images were drawn from LTM, for instance of a local market, or the sound of the ex-British Prime Minister Margaret Thatcher's voice, there was evidence for only minimal involvement of the loop and sketchpad. We concluded that a vivid image is one that has the potential for retrieving sensory detail; when the detail depends on STM, the loop and sketchpad will set the limit to such information, and hence of the rated vividness of the image. When the image is based on LTM, however, the role of the loop and sketchpad is much less important. When I form an image of my local market, for example, I "see" a particular flower stall, a stallholder, and an array of flowers. This almost certainly represents a construction based on the accumulated experience of the stall over many years, rather than a detailed representation

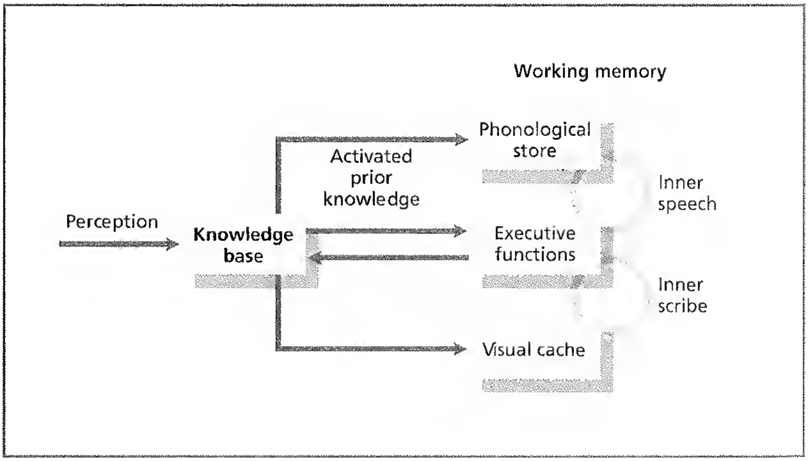


Figure 3.8 Logie's version of the multicomponent working memory model in which the visual cache is the counterpoint to the phonological store, and the inner scribe is an active rehearsal process that is the visuo-spatial counterpoint of subvocal speech. From Logie and van der Meulen (in press), based on Logie (1995).

of a particular display. Our evidence suggests however that this representation does not depend very crucially on the sketchpad, so where is it held? We shall return to this point when we discuss the fourth component of working memory, the **episodic buffer**.

Logie (1995) has proposed a structure for the visuo-spatial sketchpad that is somewhat analogous to that of the phonological loop, namely a passive store that he terms the **visual cache**, and an active spatial rehearsal process, the *inner scribe* (Figure 3.8). He proposes that the system provides a visuo-spatial workspace for performing complex tasks, but somewhat more controversially argues that it is always fed by LTM.

THE CENTRAL EXECUTIVE

Working memory is assumed to be directed by the central executive, an attentional controller rather than a memory system. Its main mode of operation is assumed to be that proposed by Norman and Shallice (1986), who assumed two modes of control, one of which is automatic and based on existing habits whereas the other depends on an attentionally limited executive. Driving a car would be an example of the first type of semi-automatic control. The activities involved can be relatively complex, so that potential conflicts can occur, for example between continuing to drive and slowing down in response to a traffic signal, or another driver entering the road. There are assumed to be well-learned procedures for resolving such conflicts automatically. Because such behavior is based largely on well learned habits, it requires little attention. Have you ever had the somewhat worrying experience of arriving at your driving destination with no recollection of how you got there? Were you conscious during the trip? You almost certainly were, but thinking about other matters and leaving the routine decisions to your conflict-resolution system.

However, when automatic conflict resolution is not possible, or when a novel situation arises, for example, a road is closed for repairs, then a second system is called into action, the **supervisory attentional system (SAS)**. This is able to intervene, either in favor of one or other of the competing options or else to activate strategies for seeking alternative solutions. It is the SAS component that is assumed to be crucial to the central executive.

Donald Norman and Tim Shallice had somewhat different purposes in jointly producing their model. On the one hand, Norman was interested in slips of action, whereby a lapse of attention produces unforeseen consequences. These are sometimes trivial, as when you set off on a Saturday morning to drive to the grocery store and find yourself taking your regular route to work instead. On other occasions, such slips of attention can have tragic consequences, as when pilot error can lead to a plane crash. Both of these reflect situations in which the SAS fails to operate when it should.

Shallice, on the other hand, was principally interested in patients with frontal lobe damage, who appear to have problems of *attentional control*. This is sometimes reflected in perseveration, repetitively performing the same act or making the same mistake repeatedly. Patient RR, for example (Baddeley & Wilson, 1988), was asked during an occupational therapy session to measure and cut a series of lengths of tape. He persistently grasped the tape at the wrong

KEY TERMS

Episodic buffer: A component of the Baddeley and Hitch working memory model, which assumes a multidimensional code, allowing the various subcomponents of working memory to interact with long-term memory.

Visual cache: A component of Logie's model of visual working memory. It forms a counterpart to the phonological store and is maintained by the inner scribe, a counterpart to phonological rehearsal.

Supervisory attentional system (SAS): A component of the model proposed by Norman and Shallice to account for the attentional control of action.

point, leaving very short tape lengths. When this was pointed out, he crossly responded "I know I'm getting it wrong!" but was unable to break out of the incorrect action sequence.

On other occasions, the same patient might continually fail to *focus* attention, simply responding to whatever environmental cues are present. This sometimes leads to what is known as *utilization behavior*, in which the patient uninhibitedly makes use of whatever is around, drinking the tester's cup of tea for example, or on one occasion picking up a hypodermic syringe and attempting to inject the examining doctor. In the absence of control from the SAS, the patient simply responds to any cues or opportunities afforded by the environment. The frontal lobes are assumed to be the part of the brain necessary for adequate operation of the SAS, with damage potentially leading to failures in the attentional control of action, particularly when the damage is extensive and extends to both the right and left frontal lobes.

Another function of the frontal lobes is to *monitor* behavior, checking that it is appropriate. Failure to do this can lead to bizarre behavior or **confabulation**. Patient RR, for example, woke up in bed on one occasion and demanded from his wife, "Why do you keep telling people we are married?", "But we are" she said, "we have three kids," going on to produce the wedding photographs. "That chap looks like me but it's not because I am not married," the patient replied. An hour or so later he appeared to have forgotten the incident and strongly denied it (Baddeley & Wilson, 1986).

A major function of the central executive is that of attentional focus, the capacity to direct attention to the task in hand. Consider a complex task like playing chess. What is the role of working memory? One approach is to use concurrent tasks to disrupt each of the subcomponents of working memory. Holding (1989) showed that counting backwards disrupted the capacity of players to remember a chess position, concluding that verbal coding was important. However, counting backwards also demands executive processing. Robbins, Anderson, Barker, Bradley, Fearneyhough, Henson et al. (1996) therefore compared the effects on the recall of chess positions of articulatory suppression, spatial tapping, and an attentionally demanding task known as random generation, in which participants try to produce a stream of numbers, making the sequence as random as possible. We tested both highly expert and relatively inexperienced players. The two groups differed greatly in overall performance, but all showed the same interference pattern. Articulatory suppression had no influence, suggesting that the phonological loop was not involved, whereas the visuo-spatial task did impair performance but not as much as random generation. We found the same result when the task was changed from remembering the chess positions to choosing the best next move, indicating an important role for both the sketchpad and central executive in planning as well as remembering a chess position.

Another attentional capacity that is attributed to the central executive is that of dividing attention between two or more

According to Robbins et al. (1996), selecting good chess moves requires use of the central executive and the visuo-spatial sketchpad, but not of the phonological loop.

KEY TERM

Confabulation: Recollection of something that did not happen.

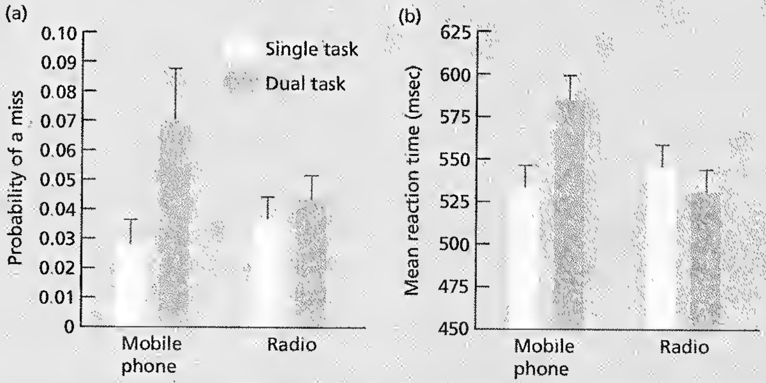
tasks, for example chatting to a passenger while driving. On the whole, this seems to proceed reasonably safely. If the traffic situation becomes complex, the driver can cease speaking and the passenger is likely to see why, and postpone the conversation. This is not the case with a cell phone conversation, however, during which there might also be a much more serious attempt to convey complex information or discuss an important business matter. As we saw in the section on the sketchpad, if spatial information is involved, this is likely to interfere with steering control. Even more important, however, is the effect of concurrent telephoning on the capacity to make sensible driving decisions. Brown, Tickner, and Simmonds (1969) had their participants drive a route marked out on an airfield that involved going through gaps of varying width between polystyrene blocks. A concurrent verbal reasoning task did not impair the drivers' skill in steering through such gaps, but it seriously disrupted their judgment with the result that they tended to attempt gaps that were narrower than the car. The danger in telephoning while driving does not principally result from what the driver's hands are doing but from what the brain is neglecting to do (Box 3.3).

Studies of patients with Alzheimer's disease suggest that they find dividing their attention across tasks particularly hard. One study (Baddeley, Bressi, Della Sala, Logie, & Spinnler,

Box 3.3 Inattention when driving causes accidents

A naturalistic study that videoed drivers and the road ahead for a total of 2 million miles of driving time recorded 82 crashes, with 80% implicating driver inattention during the previous 3 seconds (National Highway Safety Administration, 2006). Cell (mobile) phone use is a potent source of such inattention, with accidents being four times more frequent when a cell phone is in use, regardless of whether it is hand held (Redelmeier & Tibshirani, 1997).

A laboratory study by Strayer and Johnston (2001) showed that drivers who were using cell phones were substantially more likely to miss a red light (panel a) and were significantly slower at applying the brakes (panel b), regardless of whether or not the phone was hand held. From Strayer and Johnston (2001). Copyright © Blackwell Publishing. Reproduced with permission.



1991a) compared the capacity to combine activities across three groups: Alzheimer patients and elderly and young control participants. Two tasks were used, a tracking task and a digit span task. The experiment began by ensuring that the three groups were performing at the same level. This involved establishing digit span and tracking skill for each participant, and resulted in the use of somewhat shorter digit sequences and slower target speeds in the patients and elderly controls. At this point, we required all groups to perform both tasks at the same time. We found that the normal elderly and young groups showed a similar modest drop in performance under combined conditions, whereas the Alzheimer patients showed a marked deficit. Subsequent research showed that this was not a result of simply increasing the cognitive load as our patients showed a clear dual-task deficit even when the two tasks were made very simple. Furthermore, this differential deficit did not occur with single tasks—even when they were made more difficult, patients and controls responded in a very similar way (Logie, Cocchini, Della Sala, & Baddeley, 2004). A practical implication of this finding is that such patients might be able to follow a conversation with one person quite well, but lose track when more people take part (Alberoni, Baddeley, Della Sala, Logie, & Spinnler, 1992).

It has been suggested that the central executive is required if attention has to be switched between two or more tasks (Baddeley, 1996). However, the idea that switching might always be the function of a single attentional system appears to be an oversimplification, with some aspect of switching being relatively automatic whereas others are almost certainly attentionally demanding (Allport, Styles & Hsieh, 1994; Monsell, 2005).

THE EPISODIC BUFFER

A major problem with the three-component model of working memory was that of explaining how it was linked to LTM. Memory span for words in a sentence is about fifteen compared to a span of five or six for unrelated words (Brener, 1940). However, it is not clear how this can be accounted for within the three-component model. Fifteen words are substantially more than the capacity of the phonological loop, and enhanced recall of sentences is not limited to those that can readily be turned into visual imagery. At a broader level, it is of course unsurprising that this is the case. The order of words within a sentence is constrained by the rules of grammar and by the overall meaning of the sentence, both allowing the chunking process described in Chapter 2 to increase span, and in both cases depending on LTM. However, this then raises the question of exactly how working memory is able to take advantage of long-term knowledge: How do working memory and LTM interact?

This was by no means the only problem for the three-component model. Digit span itself presents a challenge. Given that we can typically remember seven or more digits, and two or three of these come from the loop, where are the other items stored? If in visual STM, how is this combined with phonological STM? Finally, as we noted in the Baddeley and Andrade study of the vividness of imagery described in Chapter 2, those images that are based on LTM such as that of a familiar market scene do not appear to depend at all heavily on the visuo-spatial and phonological subsystems. So where is the information for such complex images held while the judgment of vividness is made? In an attempt to provide an answer to these questions, I proposed a fourth component, the episodic buffer (Baddeley, 2000).

The episodic buffer is assumed to be a storage system that can hold about four chunks of information in a multidimensional code. Because of its capacity for holding a range of dimensions, it is capable of acting as a link between the various subsystems of working memory, also of connecting these subsystems with input from LTM and from perception. Each of these information sources uses a different code, but these can be combined within the multidimensional buffer.

I also proposed that information was retrieved from the episodic buffer through conscious awareness. This linked the working memory model with an influential view as to the function of consciousness. Baars (1997, 2002) suggests that conscious awareness serves the function of pulling together separate streams of information from the various senses and **binding** them into perceived objects and scenes. He links this to the proposal that consciousness serves as a mental workspace that assists in performing complex cognitive activities, in short, a working memory. He uses the metaphor of a theater, in which consciousness is represented by the stage on which an ongoing play is played by actors, who are seen as analogous to the various interactive cognitive processes.

In its initial form (Baddeley, 2000), the episodic buffer was assumed to be an active system, entirely controlled by the central executive. It was assumed to be capable of binding together previously unrelated concepts, to create new combinations, for example, combining the concepts of ice hockey and elephants, to imagine an ice-hockey-playing elephant. This novel representation can be manipulated in working memory, allowing one to answer questions such as what position the elephant should play. It could, for instance, do some crunching tackles, but might it be even more useful in goal?

At a more routine level, it was suggested that executive processes were necessary to bind the words in a sentence into meaningful chunks, or indeed to bind perceptual features such as shapes and colors into perceived objects. If this was the case, then one would expect that disrupting the executive with a demanding concurrent task would interfere with binding. More recent evidence suggests that this is probably not the case. A demanding concurrent task impairs STM for shapes and colors but does not disrupt the capacity to bind this information into colored objects (Allen, Baddeley, & Hitch, 2006). Similarly, disrupting the executive impairs immediate memory for both unrelated word lists and sentences, but does not reduce the capacity to bind or chunk the words into sentences (Allen & Baddeley, 2008).

If this preliminary evidence is sustained, it would suggest a change in the model of consciousness proposed from the theater analogy in which the episodic buffer is the centre of an *active* binding process to a more passive system: A screen on which information from a range of sources is displayed, with the active process of combination proceeding off-screen.

The concept of an episodic buffer is still at a very early stage of development, but has already proved useful in a number of ways. At a theoretical level, it bridges the gap between the multicomponent Baddeley and Hitch (1974) model with its emphasis on storage, and more attentionally focused models such as that of Cowan (1999, 2005). In doing so, it has emphasized the important question of how working memory and LTM interact, and more specifically has stimulated research on the issue of how different sources of information are bound together. This has led to further links between the multicomponent model and studies concerned with visual attention and memory (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001), and with the classic issues of language comprehension (Daneman & Carpenter, 1980; Kintsch & van Dyck, 1977).

The current model of working memory is shown in Figure 3.9. This is essentially an elaboration of the original three-part model, with two major changes. One of these reflects the assumed link to LTM from the phonological and visuo-spatial subsystems, one allowing the acquisition of language, and the other performing a similar function for visual and spatial information. This is much less investigated than is the language link, but is assumed to be involved in acquiring visual and spatial knowledge of the

KEY TERM

Binding: Term used to refer to the linking of features into objects (e.g. color red, shape square, into a red square), or of events into coherent episodes.

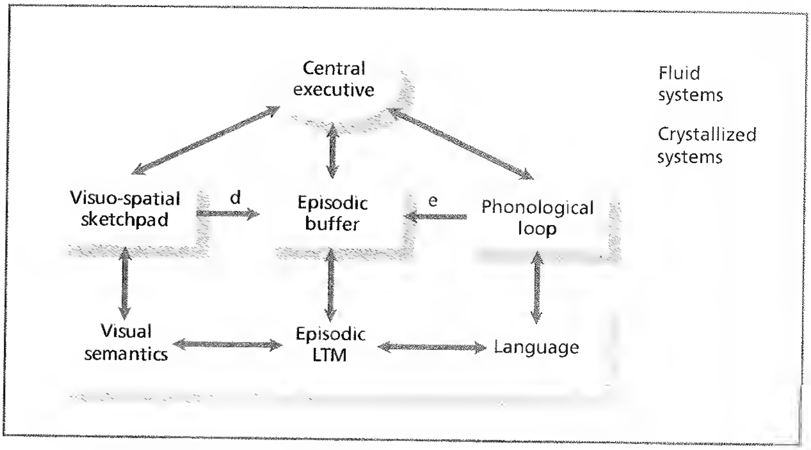


Figure 3.9 The Baddeley (2000) version of the multicomponent working memory. Links to long-term memory have been specified and a new component, the episodic buffer, added.

world, for example learning the shape and color of a banana, or the layout of a city.

The second major change is the inclusion of the episodic buffer. In the original version of the buffer (Baddeley, 2000) it was accessed only through the central executive. However, the evidence just described on binding visual and verbal information into chunks suggests that information can access the buffer directly from the visuo-spatial and phonological subsystems and from LTM (arrows d and e). Finally, an even more recent attempt to account for the way in which emotion influences working memory also assigns a major role to the episodic buffer (Baddeley, 2007).

However, although the multicomponent model has thrived in the 30 years since it was proposed, it is by no means the only model of working memory. Indeed, a great deal of research on working memory, particularly in North America, has used a very different approach, less influenced by studies of STM and data from neuropsychological patients and strongly influenced by methods based on individual differences between normal participants.

INDIVIDUAL DIFFERENCES IN WORKING MEMORY

This approach to working memory was sparked by a study by Daneman and Carpenter (1980), who were interested in the possible role of working memory in language comprehension. They took as the defining feature of working memory, the need for the simultaneous storage and processing of information, and then set out to develop a task that would measure this. They proved remarkably successful. The task they produced appears to be a very simple one. Participants are required to read a series of sentences and subsequently recall the last word of each. Try it for yourself:

A sailor returned from a long voyage having acquired a parrot as a pet.

It was a terribly cold winter with many violent storms.

The play was an enormous success and ran for many years.

What were the three last words?

They were *pet, storms, years*. Span is typically between two and five sentences.

Daneman and Carpenter (1980) showed that their working memory span task was able to predict the prose comprehension capacity of their student participants, a result that has been replicated many times. Daneman and Merikle (1996) review 74 studies showing broadly similar results. A total of 38 studies looked at working memory span and global comprehension, finding an average correlation of .41; another 36 studies using more specific language processing measures found an average correlation of .52. In both cases, correlations were higher than those obtained for verbal STM tasks (.28 and .40, respectively).

Working memory span has also proved able to predict a wide range of other capacities. High-span participants are better at prose composition (Benton, Kraft, Glover, & Plake, 1984), obeying complex instructions (Engle, Carullo, & Collins, 1991), and taking notes (Kiewra & Benton, 1988). The capacity to predict performance extends beyond language tests to performance on a course concerning logic gates (Kyllonen & Stephens, 1990), and on a 40-hour long course on the PASCAL programming language (Shute, 1991). A study by Kyllonen and Christal (1990) compared performance on a series of working memory tasks with a battery of reasoning ability measures taken from standard IQ tests, finding a very high correlation. The principal difference was that the IQ tests appeared to depend somewhat more on prior experience, and the working memory measures somewhat more on speed. Engle, Tuholski, Laughlin, and Conway (1999) obtained a similar result finding a high correlation between working memory and fluid intelligence.

Variants of the working span task are already being applied to practical problems. They form an important component of a battery of tests developed by Susan Gathercole and Susan Pickering based on the multicomponent working memory model, which they have applied to detecting and predicting learning problems in school-age children (Gathercole & Pickering, 2000a). Their test battery has separate measures of phonological loop and sketchpad performance based on tasks involving verbal or visuo-spatial STM, together with what they term *complex span* tasks—visual and verbal processing tests that, like the Daneman and Carpenter task, involve simultaneously storing and manipulating information and hence tap the central executive.

Analysis of the performance of school-age children is broadly consistent with predictions from the multicomponent model, allowing the separate components of working memory to be estimated and related to academic performance. Children who have been identified as having special educational needs perform poorly overall on the working memory battery (Gathercole, Pickering, Knight, & Stegmann, 2004b). Scores on specific subtests are also informative, with delayed reading and arithmetic being associated with poor performance on both phonological STM and complex span tasks in 7- to 8-year-old children (Gathercole & Pickering, 2000b), whereas complex span continues to predict maths and science scores at the age of 14 (Gathercole, Lamont, & Alloway, 2006).

What are children with poor working memory performance like? Gathercole's group decided to sit in on classes and observe how these children differed from their classmates. Children with low working-memory scores were typically described by their teachers as "dreamy" or inattentive; not disruptive, but failing to follow instructions and to do the right thing at the right time. Gathercole et al. noted, however, that the instructions were often quite complex, for example "Put your reading cards back in the envelope, your pencils back in the box, and then sit on the carpet in the corner." The child would begin the task and then apparently lose track. The children themselves reported that they forgot. However, this memory problem was not something that the teacher typically realized.

It later became clear that a good number of these children were diagnosed with ADHD (attention deficit hyperactivity disorder), which, as its name suggests, has two potentially separable components of which one—attention deficit—might well be linked to working memory performance. This is being investigated by Gathercole's group, which has developed a program to enable teachers to identify children with problems based on

Gathercole et al. found that children with low working memory scores were typically described by their teachers as "dreamy" or inattentive; however ADHD may well be responsible as it is linked to working memory performance.
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working-memory limitations and to modify their teaching accordingly (Gathercole & Alloway, 2008).

THEORIES OF WORKING MEMORY

Given the predictive power of complex span measures, there is great interest in understanding why they are successful. Attempts to develop a theory of working memory based on individual differences typically involve breaking working-memory performance down into a number of more basic components, devising tasks that aim to tap these components, and then examining the extent to which each of these is able to predict performance on tests of reasoning, intelligence, or academic performance. Part of this process of analysis involves studying the extent to which particular tasks are related to each other, in ways that might suggest the nature of the underlying structure of the memory and processing systems involved.

Happily, there tends to be broad agreement, with most analyses stressing the importance of an attentionally based control system, analogous to the central executive within the multicomponent working memory model. This tends to be strongly involved in complex tasks, with a smaller contribution from two or more components that appear to be responsible for the simple storage of verbal and visuo-spatial material, respectively (Engle et al., 1999; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; Gathercole, Pickering, Ambridge, & Wearing, 2004a). Again, this broadly resembles the structure proposed by the Baddeley and Hitch model. Most theories of working memory focus on the executive component, often simply attributing the STM functions to relatively unspecified "activation of LTM," although the use of active verbal rehearsal is typically accepted as a source of temporary storage.

Although most theories derived from the study of individual differences have proved to be broadly compatible with the multicomponent model, this resemblance is not always obvious. Nelson Cowan's influential approach to working memory is a good example of a conflict that is more apparent than real (Baddeley, 2001, 2007; Cowan, 2001, 2005).

Cowan's embedded processes theory

Cowan described working memory as "cognitive processes that retain information in an unusually accessible state" (Cowan, 1999 p. 62). For Cowan, working memory depends on activation that takes place within LTM, and is controlled by attentional processes (Figure 3.10). Activation is temporary and decays unless maintained either through active verbal rehearsal or continued attention.

Activated memory is multidimensional, in that way resembling my own development of the concept of an episodic buffer, the main difference being that I assume that items are downloaded from LTM and represented within the episodic buffer, whereas Cowan suggests that the "addresses to locations in LTM are held." It is not clear at this point how one would distinguish between these two views. The main consequence is a differential

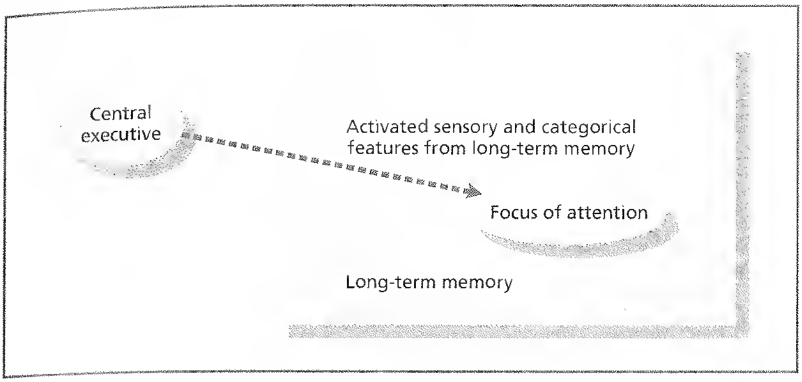
Central executive
Activated sensory and categorical features from long-term memory
Focus of attention
Long-term memory

Figure 3.10 Cowan's embedded-processes model of working memory. A central executive controls focus of attention, which acts on recently activated features from long-term memory. The focus can hold approximately four objects in mind at the same time. Adapted from Cowan (1988).

emphasis, with Cowan being particularly concerned with working memory *capacity* where he argues strongly for a capacity of four chunks (Cowan, 2005), rather than the seven originally proposed by Miller (1956). This influence reflects Cowan's interest in attention, and in the development of memory during childhood rather than in the more peripheral aspects of working memory and the neuropsychological evidence that have featured prominently in my own approach. The importance of a verbal subsystem is certainly not denied by Cowan, who has in fact done important work on phonological STM (e.g. Cowan, 1992; Cowan et al., 1992), although his theory is less concerned with its detailed modeling.

Engle's inhibitory control theory

One of the most active and innovative groups using the individual differences approach to working memory is that associated with Randy Engle and colleagues. Whereas much of the work using the working-memory span measure has been limited to observing correlations between span and various cognitive capacities, Engle has consistently focused on the theoretical issue of understanding what capacities and processes underpin such associations.

Turner and Engle (1989), for example, demonstrated that the predictive capacity of complex span was not limited to measures based on sentence processing. They developed the *operation span* measure in which each to-be-remembered word is followed by arithmetic operations; for example, *Apple*, 7 + 2 – 1 = ? *House*, 5 – 1 + 6 = ? and so on; the words are then recalled. This measure correlates highly with the initial-sentence span task and is also is a good predictor of cognitive performance.

Engle (1996) proposes that performance on a complex span task is made difficult by the need to protect the memory of the presented items from *proactive interference (PI)*, the tendency for earlier items to compete at retrieval with the items to be recalled. Evidence for this comes from a range of sources and is typically based on a procedure whereby a complex span task is given to a large group of students, with those performing particularly well or particularly badly then being chosen for further investigation. Then, rather than looking for an overall correlation across participants, Engle tests for differences between these two extreme groups in their capacity to perform various other tasks.

In one study, participants were required to remember three successive free recall lists, each comprising one word from each of ten semantic categories, for example one animal, one color, one country. As expected, use of the same categories but different instances across successive trials led to poorer recall of later lists. As predicted (Kane & Engle, 2000), this interference effect proved to be reliably greater in low working-memory span participants. Performance on the first list did not differ, suggesting that resistance to interference rather than learning capacity was the crucial factor.

Engle suggests that the capacity to resist interference is not limited to memory. In one study Conway, Cowan, and Bunting (2001) required participants to repeat a stream of digits presented to one ear and ignore messages presented to the other. Unexpectedly, the person's name was included in the unintended stream. When subsequently questioned, the low span participants were much more likely to have detected their names, even though instructed to ignore that source, presumably because they were less able to shut out the irrelevant material, as predicted by the **inhibition** theory (Conway et al., 2001).

These and other studies do indeed suggest that there is a genuine and important link between complex span and capacity to resist interference, although it is entirely plausible to assume that both reflect some kind of more general executive capacity that plays an equally important role in other cognitive functions. However, the nature of inhibition is itself open to question. A study by Friedman and Miyake (2004) found evidence for two types of inhibition, one reflecting a capacity to inhibit a powerful response tendency, such as moving your eyes to fixate a visual target, and the other a quite separate inhibition effect, reflecting interference within memory. Both were modestly related to the Daneman and Carpenter reading span measure: For prepotent response inhibition the correlation was .23, whereas resistance to inhibition in memory correlated .33.

The time-based resource-sharing model

Whereas Engle and colleagues focus on the importance of interference with the remembered words, an alternative possibility is that complex span reflects the capacity to prevent the decay of the memory trace through rehearsal. This does not necessarily mean subvocal rehearsal, but simply "keeping in mind" the items, perhaps by intermittently focusing attention on the fading trace. Evidence for such rehearsal comes from the observation that short-term forgetting in the Peterson task is present when the delay following the three consonants to be remembered is filled by a demanding backward counting task, but not when simple articulatory suppression is required (Baddeley, Lewis, & Vallar, 1984a). This suggests that participants can maintain the items in some way without needing to continue to verbalize them.

The **resource-sharing** hypothesis was been developed by a French group involving Pierre Barrouillet and Valerie Camos, who replaced the arithmetic task used in Turner and Engle's (1989) operation span task with a simple letter-reading task that was, however, strictly paced. Thus, participants were required to remember words while concurrently processing letters coming rapidly one after the other. This apparently simple task correlated even more highly with measures of reading and arithmetic than did conventional complex span measures (Lépine, Barrouillet, & Camos, 2005). Barrouillet et al. (2004) explained this, and other related findings, by arguing that more complex tasks allow brief gaps in which rehearsal might occur, whereas their more rigidly controlled simple task minimizes such rehearsal.

A related theory is the **task-switching** hypothesis proposed by Towse and Hitch (1995; Towse, Hitch, & Hutton, 2000), who also assume a trace decay interpretation with participants switching

KEY TERMS

Inhibition: A general term applied to mechanisms that suppress other activities. The term can be applied to a precise physiological mechanism or to a more general phenomenon, as in proactive and retroactive inhibition, whereby memory for an item is impaired by competition from earlier or later items.

Resource sharing: Use of limited attentional capacity to maintain two or more simultaneous activities.

Task switching: A process whereby a limited capacity system maintains activity on two or more tasks by switching between them.

attention between maintaining the trace and performing the secondary task.

In conclusion, although there is no doubt that complex span is a very powerful predictor of a wide range of cognitive performance, we still do not fully understand why. Given the importance of this issue, it continues to be an area of great research activity.

Long-term working memory

Ericsson and Kintsch (1995) proposed a theory of **long-term working memory**. This refers to the use of LTM to assist in temporary storage. It includes the use of long-term knowledge to assist prose recall but was also strongly influenced by Ericsson's interest in the performance of people who have a specific expertise in remembering. In one study, Chase and Ericsson (1982) repeatedly tested the digit span of an individual over many days of practice, finding that his span grew and grew, eventually reaching a span of around 80 digits. On questioning him, they discovered he had developed a special mnemonic technique. He was an enthusiastic runner and had developed a system of coding the number sequences in terms of running times for particular distances and levels of performance; for example, *a very fast time for the 800 meters*. Another example came from the expert memory of a waiter who used a particular structure to memorize the orders of his customers (Ericsson & Polson, 1988). The use of the visual image of an abacus by the expert calculators discussed earlier would be another example of long-term working memory. It does not, therefore, represent an overall theory of memory but rather a particular use of LTM, which is discussed further in Chapter 16 on improving your memory.

THE NEUROSCIENCE OF WORKING MEMORY

This chapter has focused on the psychology of working memory based almost entirely on behavioral methods of study. However, an enormous amount of work has been concerned with investigating the anatomical and neurophysiological basis of working memory. Initially, this approach relied principally on the type of neuropsychological evidence; more recently, two further methods have become prominent: single-cell recording in monkeys, and neuroimaging studies based on normal human participants.

Single-cell recording approaches to working memory

Single-cell recording involves placing electrodes in individual cells within the brain of an awake monkey and then recording the cells' activity as a function of a range of presented stimuli. The method was pioneered by Hubel and Weisel (1979), who were awarded the Nobel prize for their work on the analysis of visual processing using single-cell recording. This method was extended to the study of memory by Fuster (1954) and by Patricia Goldman-Rakic (1988), who carried out a series of classic studies in which monkeys were taught to fixate a central point on a screen, maintaining their gaze while a peripheral light stimulus was presented in one of several locations. If they maintained fixation until a recall signal, and then moved their eyes to the appropriate location, they received a reward. Funahashi, Bruce, and Goldman-Rakic (1989) detected cells within the frontal lobe of the monkey that were active during this retention period. If activity continued until the recall signal, a correct response was typically made, whereas discontinued activity was followed by forgetting. This led some commentators to identify the particular area

KEY TERM

Long-term working memory: Concept proposed by Ericsson and Kintsch to account for the way in which long-term memory can be used as a working memory to maintain complex cognitive activity.

in the frontal lobe as *the* source of working memory. However, later work has identified cells behaving in a similar way in other parts of the brain (Goldman-Rakic, 1996), suggesting that the frontal areas were part of a more general system, as would indeed be predicted by a multicomponent model of working memory.

A behavioral version of this task has been developed for use with human participants, with schizophrenic patients being found to be impaired (Park & Holzman, 1992). This has caused some excitement, because of the potential link between an important disease and a very specific neurophysiologically related measure. However, although this certainly does indicate a deficit in working memory in schizophrenic patients, the effect is not particularly dramatic and other deficits, such as those in episodic LTM, are probably more important from a practical viewpoint (McKenna, Ornstein, & Baddeley, 2002). However, it seems likely that single-unit recording methods of studying memory will continue to provide an important link between psychological and neurobiological approaches to memory.

Neuroimaging working memory

A closer and more extensive link between psychological and neurobiological approaches to memory is provided by a rapidly growing body of work applying the various techniques of brain imaging described in Chapter 1 to the study of working memory. The initial studies used positron emission topography (PET), which you might recall involves introducing a radioactive substance into the bloodstream and using this to monitor the amount of activity occurring in different brain regions. Two groups were particularly active in applying this method to the study of working memory. In London, Paulesu, Frith, and Frackowiak (1993) carried out a study that was based on the phonological loop hypothesis. They identified two separate regions, one in the area between the parietal and temporal lobes of the left hemisphere, which appeared to be responsible for phonological storage, and a second more frontally based region known as Broca's area, known to be involved in speech production but that appeared to be linked to subvocal rehearsal (Figure 3.11).

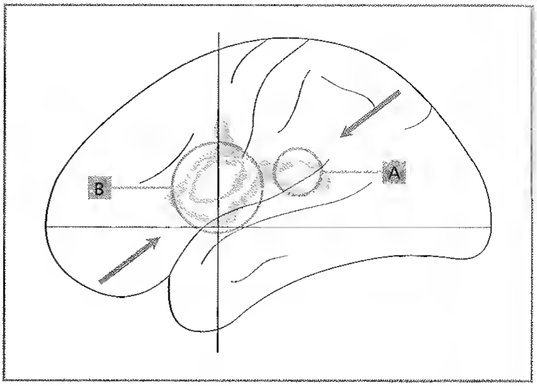

Figure 3.11 Neuroimaging the phonological loop. A study using positron emission tomography identified area A with phonological storage and area B with the articulatory rehearsal process. Redrawn from Paulesu et al. (1993).

The second group, led by John Jonides and Edward Smith at the University of Michigan, has been particularly active in using neuroimaging to investigate working memory, carrying out a sustained series of carefully designed and theoretically targeted experiments (Smith & Jonides, 1997). The first direct comparison of visual and verbal working memory was provided by Smith, Jonides, and Koeppe (1996). In their verbal memory task, participants were shown four letters, followed by a probe letter. Participants had to decide whether the probe letter had been contained in the previous set of four. A baseline control involved presenting both the stimulus and the probe simultaneously: everything was the same except for the need to remember. If the amount of brain activation in this baseline condition is subtracted from the activation involved when memory is also required, then the difference in blood flow should reflect the additional demand made by the need to remember, over and above that involved in perceiving and processing the experimental stimuli. Like Paulesu et al., Smith and colleagues found that

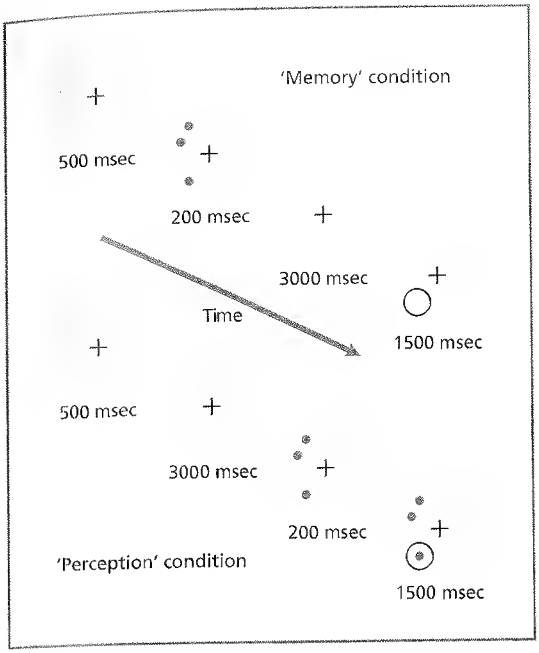

Figure 3.12 Schematic drawing of the events on each trial of the spatial memory and spatial perception tasks used by Smith et al. (1996). Copyright © Oxford University Press. Reproduced with permission.

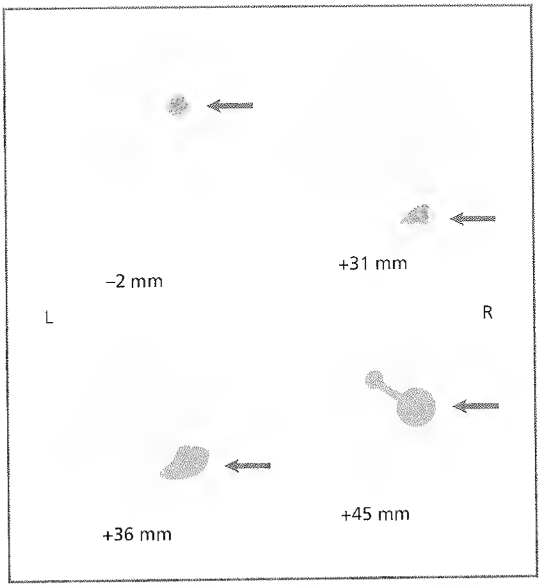

Figure 3.13 Illustration depicting PET images of the four areas activated in the visuo-spatial working memory study. Based on Smith et al. (1996).

verbal STM activated two separate areas in the left hemisphere.

In the case of visuo-spatial memory, participants were shown an array of three dots, followed after a delay by a circle (Figure 3.12). They had to decide whether this coincided with the location of one of the dots. Again, a baseline was established in which the dots and circle were presented at the same time. As indicated in Figure 3.13, visual memory resulted in activation in a series of areas in the right hemisphere (Smith et al., 1996).

Further studies (reviewed by Smith & Jonides, 1997) observed a distinction between spatial working memory as described above, and memory for an *object or pattern*, such as an abstract shape. Spatial memory activates more dorsal or upper regions of the brain whereas object memory tends to be more concentrated on lower or ventral areas (Figure 3.14). It is notable that research on visual processing in nonhuman primates (Mishkin, Ungerleider, & Macko, 1983), has identified two separable visual processing streams, with the dorsal stream being concerned with spatial location (*where*), and the ventral processing stream with shape and object coding (*what*).

You might recall that the concept of a central executive was strongly influenced by evidence from patients with frontal lobe damage. It is therefore unsurprising that neuroimaging evidence suggests that executive processes tend to rely heavily on frontal areas. One method of investigating this is through the N-back task, in which the participant sees a sequence of items and is required to press a button whenever a repeat occurs. The easiest condition is when the requirement is to

KEY TERMS

Spatial working memory: System involved in temporarily retaining information regarding spatial location.

Object memory: System that temporarily retains information concerning visual features such as color and shape.

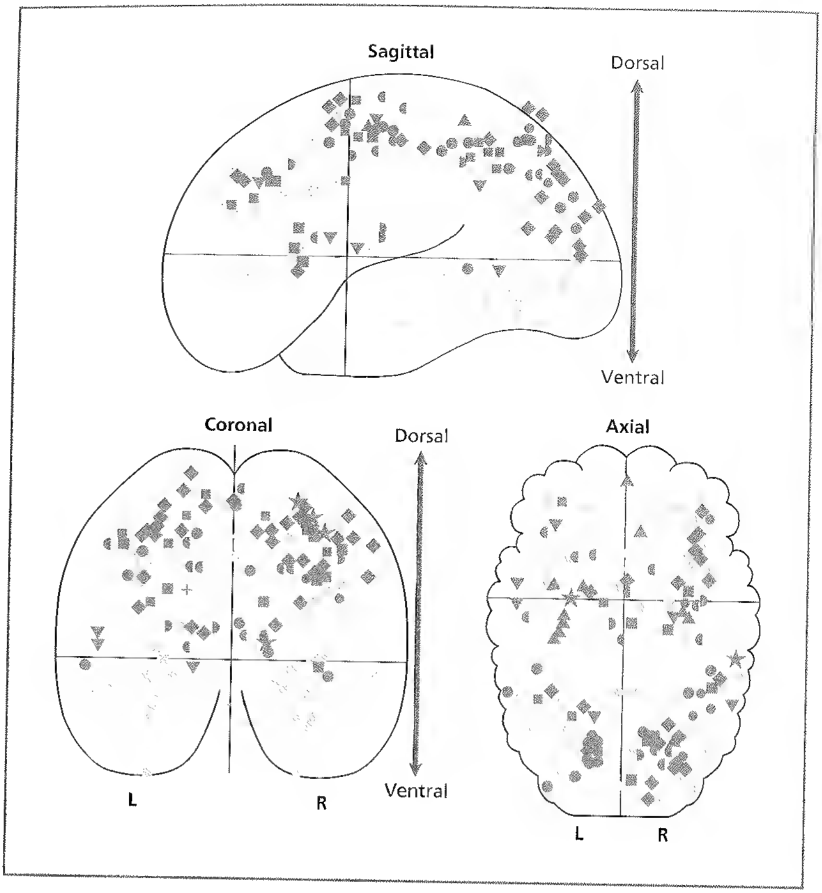

Figure 3.14 Combined data from studies involving short-term memory from visual objects (pink) or spatial location (blue). The distinction is mainly between the ventral locations for object memory, and dorsal for locations. Based on Smith and Jonides (1999).

detect immediate repeats, (e.g. 1, 7, 9, 6, 6), as minimal memory is involved. The task can be made a little harder by requiring a match between the presented item and the item presented one back (e.g. 7, 9, 6, 2, 6 where the participant should respond to the second 6). The task can be made more and more difficult by increasing the lag, as it is necessary to hold an increasingly long sequence while inhibiting each item once it is too far back. The task has a further advantage: It can be used in a broadly equivalent form to study either verbal or nonverbal visuo-spatial memory. For both the verbal and visuo-spatial N-back tasks, frontal activation occurs and increases systematically with the executive load as determined by the number of items back that need to be monitored and hence demand made on the central executive (Braver, Cohen, Nystrom, Jonides, Smith, & Noll, 1997; Owen, McMillan, Laird, & Bullmore 2005).

However, although there is no doubt that the frontal lobes play a crucial role in executive processing, there is much less agreement on the extent to which specific executive capacities are located in particular frontal areas. Some investigators have suggested the possibility of quite detailed mapping of separable executive processes (e.g. Shallice, 2002) whereas others point to the lack of consistency across studies at anything other than the broadest level (Duncan & Owen, 2000). It seems likely that settling this controversy will depend on the development of better methods at both the behavioral and neuroimaging level.

SUMMARY

The Atkinson and Shiffrin modal model, although proposed as a model of working memory, was principally based on verbal STM. It encountered problems both regarding its assumption of the transfer of information to LTM through simple rehearsal, and because of its difficulty in explaining why patients with grossly affected STM did not have general working memory problems.

Baddeley and Hitch proposed a multicomponent model of working memory comprising an attentional controller, the central executive, and two subsystems. One of these, the phonological loop, holds and manipulates speech-based information, while the visuo-spatial sketchpad performs a similar function for visual and spatial information.

Study of patient PV's very limited digit span suggested that the phonological loop might have evolved to facilitate the acquisition of language. Disrupting the loop impairs the learning of a second language. The capacity to hear and repeat back a nonword, which is assumed to depend on the phonological loop, is impaired in children with specific language problems, and provides a good predictor of level of vocabulary development in healthy young children.

The visuo-spatial sketchpad is necessary for the use of imagery both to store visuo-spatial information and also to use it to solve problems. Logie has presented a model of the sketchpad that by analogy with the phonological loop contains a store, the visual cache, and a system for spatial manipulation, the inner scribe.

Control of action by the central executive is assumed to operate along the lines initially proposed by Norman and Shallice. This involves a combination of semi-automatic control, based on existing schemas and habits, coupled with a capacity for intervention by the supervisory attentional system (SAS). The central executive is assumed to be analogous to the SAS and to be capable of both focusing and dividing attention, and to be defective in patients with frontal lobe damage.

More recently, an additional component—the episodic buffer—was proposed. This involves a multidimensional code that allows the various components of working memory to interact and to link with both perception and LTM.

Individual differences in working memory have been studied extensively using a range of measures, all based on the need to combine the storage and manipulation of information. Such measures have proved extremely successful in predicting performance across a wide range of cognitive tasks.

Theoretical interpretations of working memory are broadly consistent with the multicomponent model, but concentrate mainly on explaining the nature of the executive component. Influential theories include Cowan's embedded processes approach, strongly influenced by his interest in attention, whereas Engle and colleagues suggest that the capacity to inhibit disruptive information is crucial. A number of other groups stress the need to control the limited attentional resources as a crucial factor. This is currently a very lively area.

Neurobiological evidence has played an important role in the study of working memory. This was based initially on the study of the single neuropsychological cases, together with the study of single-cell recording in monkeys performing working memory tasks. More recently, there has been considerable research on working memory using neuroimaging techniques, producing results that are broadly consistent with both the data from patients, and the multicomponent model.

FURTHER READING

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- Atkinson, R. C., & Shiffrin, R. M. (1971). The control of short-term memory. *Scientific American*, *225*, 82–90. A good summary of the modal model for the general scientific reader.

- Cowan, N. (2005). *Working memory capacity.* Hove, UK: Psychology Press. A recent overview of Cowan's approach to working memory. It proposes that the capacity of working memory is four chunks, rather than Miller's magic number seven.

- Engle, R. W., Cantor, J., & Carullo, J. J. (1992). Individual differences in working memory and comprehension: A test of four hypotheses. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*, 972–992. Discusses a range of hypotheses about working memory and the methods for evaluating them.

- Fletcher, P. C., & Henson, R. N. A. (2001). Frontal lobes and human memory: Insights from functional neuroimaging. *Brain*, *124*, 849–881. Discussion of the role played by the frontal lobes in memory from a neurological and psychological viewpoint.

- Logie, R. H. (2003). Spatial and visual working memory: A mental workspace. *Psychology of Learning and Motivation*, *42*, 37–78. An overview of the visuo-spatial aspects of working memory by one of the leading investigators in the field.